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MULTIPLE-THICKNESS GATE OXIDE FORMED BY OXYGEN
IMPLANTATION

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BACKGROUND OF THE INVENTION

The present invention relates to the manufacture of electronic devices,
10 particularly semiconductor devices, such as logic circuits, memory circuits, and/or
combinations thereof.

Electronic devices are being made that combine various types of circuits
on a single chip of semiconductor material. For example, devices are being made that
combine logic circuits with memory arrays, or various types of memory, so that higher
15 functionality can be achieved on a single chip. This type of integration often provides
lower cost, smaller size and improved reliability compared to achieving the same
functionality with a number of different chips wired together. Unfortunately, it can be
difficult to integrate the manufacture of one type of circuit with another on a single chip.

Different types of circuits might have different types of devices that
20 require different voltage inputs, and that have different thickness of gate oxide. For
example, a logic field-effect transistor ("FET") might have a different gate oxide
thickness than an electronically erasable-programmable read only memory cell, or than a
dynamic read-addressable memory ("DRAM") cell. It is generally desirable to make all
the gate oxides for all the devices on the chip in a single process step; therefore, it may be
25 necessary to make the gate oxide in some regions thinner than the gate oxide in other
regions.

A technique has been used to vary the thickness of an oxide layer grown
on a silicon wafer during a oxide growth process by implanting nitrogen into selected
regions of the silicon. The implanted nitrogen retards the growth of silicon oxide,
30 resulting in a gate oxide of diminished thickness where the nitrogen was implanted.
However, implanting nitrogen can degrade the resultant quality of the gate oxide. Gate
oxide quality is especially important, compared to an inter-metal dielectric layer, for

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example, because of the electric field gradients a gate oxide must withstand and the low current leakage that is generally desired for good device performance. The quality of the gate oxide becomes even more important as device geometry and operating voltages shrink, both of which are associated with thinner gate oxides.

5 Therefore, it is desirable to fabricate an electronic device die with multiple thicknesses of gate oxide, and it is further desirable to be able to fabricate gate oxides of superior quality, especially thin gate oxides.

SUMMARY OF THE INVENTION

10 According to the present invention a multiple-thickness oxide layer may be grown by implanting oxygen into selected regions of a substrate where a thicker oxide layer is desired. In one embodiment, oxygen is implanted into selected regions of a silicon substrate through a thin sacrificial layer at an energy between about 10-30 keV. The sacrificial layer reduces implantation damage to the underlying silicon, and is
15 stripped prior to thermal oxidation of the substrate, and the resulting oxide layer has multiple thickness and is of high quality and is suitable for a gate dielectric, for example.

In another embodiment, a polysilicon layer between about 1,000-5,000 Å thick is deposited over a gate oxide prior to implanting oxygen into selected regions of the silicon substrate. The implant energy is chosen according to the thickness of the
20 polysilicon layer to place the peak of the oxygen profile just above the gate oxide. The substrate is then annealed in a nitrogen ambient at a temperature of about 900 °C for about 30 minutes to grow a thicker oxide in the regions that were implanted with oxygen.

Implanting oxygen to increase oxide thickness can provide a differential thickness of about 5-20 Å for implant doses of between about $5 \times 10^{15}/\text{cm}^2$ - $1 \times 10^{16}/\text{cm}^2$.
25 Unlike nitrogen implantation techniques, where the thickness differential is highly sensitive to the thickness of the oxide, the present invention provides a differential thickness that is less sensitive to the oxide thickness. Additionally, the oxygen-implanted oxides exhibit superior reliability to nitrogen-implanted oxides, and even non-implanted

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BRIEF DESCRIPTION OF THE DRAWINGS

Figs. 1A-1C are simplified cross sections of a semiconductor die illustrating a fabrication sequence resulting in multiple oxide thicknesses using an oxygen

implant performed prior to gate oxidation, according to an embodiment of the present invention;

Figs. 1D-1F are simplified cross sections of a semiconductor die illustrating a fabrication sequence resulting in multiple oxide thicknesses using an oxygen implant performed after a polysilicon deposition, according to another embodiment of the present invention;

Fig. 2 is a graph illustrating the oxide thickness differential between implanted and unimplanted regions for oxygen implants and nitrogen implants versus unimplanted oxide thickness;

Fig. 3 is a graph illustrating the tunneling current characteristics of gate oxides formed in accordance with the fabrication sequence illustrated in Figs. 1A-1C and an unimplanted gate oxide;

Fig. 4 is a graph showing the capacitance versus gate voltage for the samples shown in Fig. 3;

Fig. 5 is a graph illustrating the tunneling current characteristics of gate oxides formed in accordance with the fabrication sequence illustrated in Figs. 1D-1F and an unimplanted gate oxide;

Fig. 6 is a graph showing the capacitance versus gate voltage for the samples shown in Fig. 5;

Fig. 7 is a graph of drain current versus gate voltage for various oxide layers at various drain bias voltages;

Fig. 8 is a graph of charge-to-breakdown versus stress current for relatively thin oxide layers fabricated with nitrogen implant technology and for oxide layers fabricated with oxygen implant technology of comparable thicknesses;

Fig. 9 is a graph of charge-to-breakdown versus stress current for relatively thick oxide layers fabricated with nitrogen implant technology and for oxide layers fabricated with oxygen implant technology of comparable thicknesses;

Fig. 10 is a bar chart of charge-to-breakdown at a constant stress current density for oxides of various thicknesses made using a nitrogen implantation method, oxygen implantation methods, and no implantation;

Fig. 11 is a graph of drain current degradation versus injected charge for oxide layers of comparable thickness using a nitrogen implantation technique, an oxygen implantation technique, and no implant.

DESCRIPTION OF THE SPECIFIC EMBODIMENTS

As noted above, the present invention provides an improved multiple-thickness gate oxide for transistors on a single semiconductor die.

5 Figs. 1A-1C and Figs. 1D-1E illustrate steps for two embodiments of the invention in forming multiple gate oxide thicknesses. In Fig. 1A a silicon substrate 10 has a layer of LOCOS silicon oxide 12 on a surface with a layer of photoresist formed over a portion of oxide 12 to limit implantation of oxygen at 16. Thereafter, in Fig. 1B the photoresist and thin LOCOS oxide are striped, and in Fig. 1C gate oxide, T_{OX1} and
10 T_{OX2} , are grown on the surface. T_{OX2} over the heavier implanted oxygen is thicker than T_{OX1} over the lighter implanted (or non-implanted) oxygen. Gate oxidation is carried out at 800°C followed by a two hour anneal at 500°C. Source and drain anneal is carried out later at 900°C for 30 minutes.

The steps in the second embodiment illustrated in Figs. 1D-1F are similar
15 to the steps in the first embodiment, but the oxygen implant 16 is after the polysilicon gate 18 deposition to prevent damage and contamination of the substrate. Again, photoresist 14 is utilized to vary or prevent the oxygen implant.

Previous studies of forming thicker gate oxides using large implant dose of oxygen ($-10^{17} - 2 \times 10^{18} \text{ cm}^{-2}$) have shown that severe damage occurs in the substrate,
20 casting oxygen implant as an unsuitable technique for forming gate oxides. Due to the scaling of the gate oxide, however, the thickness differentials in today's embedded circuits is less than 5 nm as illustrated in the following table:

Circuit	Gate Voltage	Gate Oxide Thickness
Logic	1.5 V	30 Å
I/O	2.5 V	50 Å
DRAM	2.0 V	40 Å
EEPROM	-8 V	80 Å

25 Fig. 2 is a graph illustrating oxide thickness without implant and the resulting oxide thicknesses with oxygen implant and with nitrogen implant. Fig. 2 shows that the oxide thickness differential created with a nitrogen implant strongly depends on

the unimplanted oxide thickness. In contrast, the thickness differential is independent of the unimplanted T_{ox} when the oxygen implant is used.

Fig. 3 plots gate voltage (V) versus gate current (A/cm^2) and illustrates the tunneling current characteristics for the gate oxide formed with oxygen implant using the process of Figs. 1A-1C. The physical thicknesses were extracted by comparing the measured current with the theoretical tunneling current and were confirmed by pairing the measured high frequency CV data with simulated results from a 1-D self-consistent Shrodinger and Poisson equations solver, as illustrated in Fig. 4. It was found that as the oxygen implant dose increases, the substrate doping level and thus $\|V_t\|$ also rises as a result of thermal donor generation from excess oxygen in the substrate. This effect can be eliminated by optimizing the anneal steps. Figs. 5 and 6 are similar to Figs. 3 and 4 and show that similar increases in oxide thickness are also achieved with oxygen implanted after polysilicon deposition. The good agreement of the measured IV and CV data with theory in Figs. 3-6 demonstrates that neither the interface nor the bulk property of the oxide is compromised by the oxygen implant.

Fig. 7 is a plot of gate voltage (V) versus drain current (A) and illustrates the subthreshold characteristics of transistors with gate oxide formed from various oxygen implant doses. No degradation in subthreshold swing or excessive leakage was observed in devices fabricated with the oxygen implant technology of the present invention.

Figs. 8 and 9 are plots of stress current (A/cm^2) versus change to breakdown ($Coul/cm^2$) and illustrate the reliability of the oxides grown by oxygen implant as compared with those formed by nitrogen implant. Figs. 8 and 9 show that 20 Å/30 Å and 30 Å/50 Å multiple oxide technologies using oxygen implant yield significantly larger Q_{BD} than the nitrogen implant technology. Fig. 10 shows that oxygen implanted oxides have even better Q_{BD} than the conventional oxide while nitrogen implanted oxides have significantly lower Q_{BD} . The Q_{BD} of each thickness group was measured at the same stress current density. In Fig. 11, oxides with the oxygen implant showed smaller drain current degradation after Fowler-Nordheim current stressing.

In another embodiment of the invention, the process illustrated in Figs. 1D-1E includes the deposition of a high dielectric constant layer at the silicon substrate surface prior to the deposition of the polysilicon gate 18. A suitable high dielectric

constant layer can be a silicon nitride, zirconium oxide, or hafnium silicate (HfSiO).
Thereafter, oxygen implantation into the silicon substrate and/or polysilicon gate
followed by annealing, as in the process of Figs. 1D-1F, will grow a very thin (<2 nm)
silicon oxide with well-controlled thickness. The thin silicon oxide can serve as the
5 buffer layer or interfacial layer that is critical to the attainment of high carrier mobility
and low interface defects. In the prior art, the buffer layer is deposited or grown in an
oxygen gas atmosphere with buffer layer thickness difficult to control.

While the above is a full description of the specific embodiments, various
modifications, alternative constructions and equivalents may be used. For example, while
10 reference is made to "O₂" implants, it is understood that the implant is done with an O⁺
oxygen ion, or other types of oxygen, such as oxygen plasma species, or radicals, or even
oxygen containing compounds, such as OH[•], might be used to implement the present
invention. Similarly, although the invention has been described in terms of a silicon
substrate, it is understood that such a silicon substrate might be a single-crystal silicon
15 wafer, a silicon-on-insulator wafer, a silicon-containing substrate, or the like. Therefore,
the above description and illustrations should not be taken as limiting the scope of the
present invention, which is defined by the appended claims.

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